Magnetic nozzle (MN) helicon plasma thruster

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Kazu’s hand-made plasma reactors

Working with 4 master course students.

Electric propulsion
Plasma physics (propulsion, space, etc…)
Industrial plasmas

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SPT-X Start to be pumped down on April 2022
Magnetic nozzle thruster includes many aspects of physics and engineering

- Thrust generation mechanisms
- Performance improvement
- Electron thermodynamics in the magnetic nozzle
- Plasma detachment from the magnetic nozzle
- Application to space debris removal
- RF engineering
Thrust

- Thrust $F$ is equal in magnitude and opposite in direction to the momentum flux exhausted from the system.
- Momentum flux $M$ of the fluid is given by sum of the static pressure $(nk_B T)$ and dynamic pressure $(mn v^2)$
  \[ F = M = (nk_B T + mn v^2) \times A \]
- For helicon thruster ($T_e >> T_i$), the ion pressure and the electron dynamic pressure would be negligible;
  \[ F = M = (nk_B T_e + m_i n u_z^2) \times A \]

**electron pressure**  **ion dynamic pressure**

The thrust is the reaction force of the ejected momentum per unit time. This force is exerted to somewhere in the thruster and somehow.
Energy/Momentum flow in the system

- Electron heating (90%)
- Circuit loss (10%)
- Ion heating (negligible)

Parallel pressure/energy:
- Loss to the radial wall (negative thrust)
- Radially directed momentum in the MN (does not affect the thrust directly)

Perpendicular pressure/energy:
- Ion dynamic momentum via a sheath (near the wall) (does not affect the thrust directly)

Momentum conversion via a magnetic expansion

Ion dynamic momentum via an electrostatic field

Plasma Production

Electrostatic Ion acceleration

DC power

RF power

RF Engineer

Atomic Processes

Magnetic nozzle
1-D dynamics of electrons and ions

Takahashi et al., POP2007
Takahashi et al., PRL2011a
Boswell et al., FPP 2015
Charles and Boswell, POP2004
Sun et al., PRL2005
Charles and Boswell, APL2003
2-D Nature of the plume in the MN

Collimated ion beam is detected. The ions seem to be deviated from the MN.

High $T_e$ electrons are generated in the source. The electrons are tied to the field lines.
Thrust

\[ F = M = (nk_B T + mnv^2) * A \]

Plasma diagnoses

Langmuir probes \(\rightarrow\) Plasma density \((n)\), Plasma potential \((V_p)\), Electron temperature \((T_e)\)
Retarding field energy analyzer \(\rightarrow\) Ion energy distribution \((\text{Beam energy}, mv^2/2)\)
Laser induced fluorescence \(\rightarrow\) Ion and neutral velocities \((v)\)
Optical emission spectroscopy \(\rightarrow\) Ion and neutral velocities \((v_i, v_n)\) and temperature \((T_i, T_n)\)

It is not easy to get the absolute values of the density, temperature, and velocity…

Thrust assessment

Thrust balance \(\rightarrow\) Absolute value of the force exerted to the thruster
Target balance \(\rightarrow\) Absolute value of the force exerted to the target
The first direct thrust measurements

Performed in Surry University
Pottinger et al., JPD 2011

F = 2.8 mN (P_{rf} = 650 W)@Kr
F/P = 4.3 mN/kW
I_{sp} = 286 sec
Efficiency = 0.6 %

Performed in the Australian National University
Takahashi et al., APL 2011

F = 3.3 mN (P_{rf} \sim 0.9kW)@Ar
F/P = 3.7 mN/kW
I_{sp} = 510 sec
Efficiency = 0.8 %
Thrust model with no B field

1-D Momentum equation (negligible electron inertia, $T_i \sim 0$, no B field)

Electron: $-eE_z = \frac{d}{dz}(p_e)$

Ion: $eE_z = \frac{d}{dz}(mnu_z^2)$

Total momentum for unit cross section (momentum flux)

Total thrust for radially uniform plasma = $(p_e + mnu_z^2)*A$

$$\frac{dT}{dz} = \frac{d}{dz}(p_e + mnu_z^2)A = 0$$

Thrust is conserved along z with no B field

$T_0 = n_{max}k_BT_e$

$T_0 = T_1$

$T_1 = nk_BT_e+mnu_z^2$

Small n, large $u_z$

Fruchtman PRL2006
Lafleur et al, POP2011

Thrust is given by the electron pressure at the maximum pressure position
Thrust model with the MN

\[ m_j \nabla \cdot (n_j v_j v_j) = q_j n_j (E + v_j \times B) - \nabla \cdot P_j \]

Integrated momentum flux (Thrust)

\[ T(z) = \iiint (p_e + mnuz^2) d\theta dr \]

\[ T_{total}(z) = 2\pi \int_0^{r_s} r p_e(r, z_0) dr \]

\[ -2\pi \int_{z_0}^{z} \int_0^{r_p(z)} r \frac{B_r}{B_z} \frac{\partial p_e}{\partial r} drdz \]

\[ -2\pi \int_{z_0}^{z} \int_0^{r_p(z)} \frac{\partial}{\partial r} (r mnuz u_z) drdz \]

* \( j_\theta \) is the electron diamagnetic current.

* ExB drift current (Hall current) is neglected for the fully magnetized model.
Individual thrust measurements

Takahashi et al., PRL 2013
Internal plasma current inducing $T_B$

\[ j_\theta = -\frac{1}{\mu_0} \frac{\partial \Delta B_z}{\partial r} + \frac{1}{\mu_0} \frac{\partial \Delta B_r}{\partial z} \]

\[ \approx \frac{1}{\mu_0} \frac{\partial \Delta B_z}{\partial r} \]

\[ J_\theta = J_{De} + J_{ExB} \]

$J_{De} \gg J_{ExB}$

Lorentz force integrated from the source exit ($z=0$).
Axial momentum lost to the radial wall ($T_w$)

Prf = 1 kW
$m_{\text{dot}} = 0.75$ mg/s
Ionization rate $\text{Xe > Kr > Ar}$

Takahashi et al., PRL2015
Density profile due to neutral depletion

Fruchtman IEEE 2008

Takahashi et al., APL2016a
Gas injection affects the profile and the thruster performance

Takahashi et al., APL2016b
Thruster model combining the global source model and the 1-D MN model

Global model inside the source
Assuming
- No radial loss of the axial momentum ($T_w$)
- No magnetic field inside the source
- $M = 1$ velocity at the open source exit

Particle balance
$K_i n_0 n_g V = n_0 u_B A_{eff}$

Power balance
$P_{abs} = e n_0 A_{eff} u_B E_T$
$A_{eff} = 2\pi RLh_R + 2\pi R^2 h_L$
$m_{dot} = M n_0 n_g v_g A_s$

Neutral density

One-dimensional magnetic nozzle model
Assuming
- Isothermal electron temperature
- Magnetized plasma expansion
- No radial loss from the magnetic nozzle

Thrust model
$T_{total}(z) = T_s + T_B$
$T_s = n_0 k_B T_e A_s$
$T_B = -\int_0^z n_p k_B T_e A \frac{\partial B_z}{\partial z'} dz'$

Plasma expansion along the magnetic flux tube
$B_{zi} A_s = B_z A = constant$

Flow velocity
$\frac{M^2 - M_i^2}{2} - \ln \left( \frac{M}{M_i} \right) = \ln \left( \frac{B_{zi}}{B_z} \right)$

Flux conservation
$n_p M u_B A = n_{exit} u_B A_s$

Lieberman and Lichtenberg, Principles of plasma discharges and material processing
Effect of the source diameter

\[ P_{rf} = 5 \text{ kW} \]
\[ C_{Ar} = 2.1 \text{ mg/s} \]
\[ L = 17.5 \text{ cm} \]

Efficiency \( \sim 10\% \)

\[ \eta_T = \frac{F^2}{2 \dot{m} P_{rf}} \]
How can we improve the performance?

1- Strong magnetic field (Electron diamagnetic thrust, $T_B$)
2- Large diameter source cavity (Particle and power balances)
3- Downstream gas injection (Density profile)

Takahashi, Sci Rep 2021
Thruster performance assessment

#Efficiency is calculated by the rf generator power

Thruster efficiency is further increased in April 2022 experiments (Kazu's Mega-HPT Labbook Vol6, page 430-431)
Plasma detachment

Electrons are still magnetized

- Magnetic field lines
- Plasma-wall interaction
- Momentum loss
- Plasma production
- Plasma heating
- Electromagnetic acceleration
- Double layer acceleration
- Ambipolar acceleration
- Hall acceleration
- Swirl acceleration
- Electron diamagnetic acceleration

Momentum conversion

Electron Larmor radius
Ion Larmor radius
Plasma radius

$r_{Le}$
$r_{Li}$
$r_{p}$

$r_{Le}$ vs. magnetic field strength (G)

$r_{Li}$ vs. magnetic field strength (G)

$r_{p}$ vs. magnetic field strength (G)

$T_e = 5eV, T_i = 0.2eV$

Cox et al., APL2008
Charles et al., PRL2009
Takahashi et al., JPD2011
Their analysis concludes

A plasma flow can detach from a spacecraft together with the field lines that become stretched along the flow. This is actually occurring around the Sun and the solar wind sometimes take their magnetic field to our Earth.

This can occur when the plasma flow energy overcomes the magnetic field energy, corresponding to the case of super Alfvénic flow ($M_A = v/v_A > 1$)

\[
\frac{1}{2} mn v^2 > \frac{B^2}{2\mu} \quad v > \frac{B}{\sqrt{\mu mn}} = v_A
\]
What should we measure to verify the stretch?

Diverged case
Negative $\Delta B_z$

Stretched case
Positive $\Delta B_z$
The first observation of the MN stretch
Measurement of the plasma-induced magnetic field $\Delta B_z$

$\Delta B_z < 0$

$\Delta B_z > 0$

FIG. 2. Spatiotemporal evolution of (a) $I_a$ and (b) $\Delta B_z$, taken for $I_B = 4.5$ A and $P_R = 5$ kW. The rf power is triggered at $t = 0$ and the signals are averaged over 16 shots, where the measurements are performed at $\sim 1200$ points ($\sim 20$ points along $z$ and $\sim 60$ points along $r$). A movie can also be found as Supplemental Material [29].
Where does the stretch occur?

$V = M_i \cdot C_s \sim 2 \text{ km/s}$
What parameter decides the stretch?

Generally, the stretch occurs for the super Alfvénic flow ($M_A = v/v_A > 1$)

The experiment shows that the stretch starts to occur at the lower Alfvén Mach Number than unity.
Force balance in an ideal MHD approximation (1)

\[ \rho (v \cdot \nabla) v = - \nabla p - \frac{\nabla B^2}{2\mu} + \frac{(B \cdot \nabla) B}{\mu}, \]

- **Inertia term**
- **Pressure force**
- **Magnetic pressure force**
- **Magnetic tension**

**Upstream limit**
1. Zero velocity \( (v \sim 0) \)
2. Straight axial magnetic field (negligible tension term)

\[ \nabla \left( p + \frac{B^2}{2\mu} \right) = 0, \]

hence
\[ p + \frac{B^2}{2\mu} = \frac{B_{vac}^2}{2\mu}, \]

**Downstream limit**
1. Low plasma pressure \( (p \sim 0) \)
2. Low magnetic field (negligible magnetic pressure)

\[ \rho (v \cdot \nabla) v = \frac{(B \cdot \nabla) B}{\mu}. \]

\[ \frac{\rho v^2}{L} \sim \frac{B^2}{\mu L}. \]

\[ v^2 \sim V_A^2 = \frac{(B_{vac} + \Delta B)^2}{m n \mu} \]

For \( v > V_{A vac} = \frac{B_{vac}}{\sqrt{m n \mu}} \)

\( \Delta B \) should be positive to maintain the equilibrium.
Force balance in an ideal MHD approximation (2)

Intermediate condition

\[ \rho (v \cdot \nabla) v = -\nabla p - \frac{\nabla B^2}{2\mu} + \frac{(B \cdot \nabla) B}{\mu}, \]

Dimension analysis

\[ \left| \frac{\rho v^2}{L} \right| \approx \left| \frac{p_e}{L} + \frac{B^2}{2\mu L} - \frac{B^2}{\mu L} \right|, \]

\[ \left| \frac{n k_B T_e}{L} - \frac{B^2}{2\mu L} \right|. \]

\[ v^2 \sim \frac{1}{2} V_A^2 - C_s^2 = \frac{1}{2} \frac{(B_{vac} + \Delta B)^2}{mn\mu} - C_s^2. \]

For \( v^2 > \frac{1}{2} V_{Avac}^2 - C_s^2 = \frac{1}{2} \frac{B_{vac}^2}{mn\mu} - C_s^2, \)

\( \Delta B \) should be positive to maintain the equilibrium.
Space debris

Debris are non-cooperative objects (uncontrollable).

The top priority is removal of large debris; Typically ~ a ton in weight, a few meter in size.
Debris removal

Contact removal

Arm capturing

Net capturing

Tether capturing

Contactless removal

Laser-based removal

the ion beam shepherd (IBS)

Two propulsion devices are required
(ion gridded thrusters)

Rubenchik et al., Light: Science and Applications, 2014

Shan et al., Progress in Aerospace Science 2016

Bombardelli and Pelaez, J. Guid. Control Dyn. 2011
Contactless debris removal using the bi-directional helicon thruster

- All the modes of acceleration, deceleration, and debris removal modes are required for the actual space mission.
- High power electric propulsion is desired for the large size debris removal.
Laboratory setup and photos

Diagram showing laboratory setup:
- Thrust balance
- Support tube
- Pivot
- LED sensor
- Solenoid
- Magnets
- Load cell
- Insulator target
- Gas inlets
- RF antenna
- Laser sensor

Graphs showing Bz (G) vs. z (cm):
- Graph 1: Shows a single peak at Bz.
- Graph 2: Shows a double peak at Bz, indicating different conditions.

Legend for Graph 2:
- (I_{BL}, I_{ER})
- (8A, 0A)
- (8A, 4A)
- (8A, 8A)
- (4A, 8A)
- (0A, 8A)
Switching the acceleration, deceleration, and debris removal modes

Takahashi, Charles, and Boswell, Scientific Reports, 2018
Continuous change in the thrust and force to the debris

The thrust and the force to the debris can be continuously changed only by the solenoid currents.

Takahashi, Charles, and Boswell, Scientific Reports, 2018
Conclusion

• The studies on the magnetic nozzle rf plasma thruster (sometimes called a helicon thruster) has been progressed over the last decade, showing many aspects of physics.

• The thruster efficiency calculated from the rf power and the thrust is approaching ~30% in April 2022.

• There seem to be further interesting physics and engineering there, e.g., the plasma detachment from the MN, the thruster design, the system development (the rf system, the gas injection system, the magnet design, etc…). Although not shown here, the electron thermodynamics is also an important topic.

• There would be common technologies between the thruster and the industrial plasmas.

• Although not shown here, the automatically- and fast-controlled frequency tunable rf system is useful for both the thruster and the plasma etching reactor.

  → e.g. AIP Advances, 11, 025013 (2021) & Front. Phys., 9, 639010 (2021)